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THE EFFECT OF A PROPULSOR ON THE HULL BOUNDARY LAYER OF A BODY OF REVOLUTION

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Summary

An axisymmetric boundary-layer prediction method has been modified to include an approximate representation of a lightly-loaded propulsor. It is shown that, given the average increase in velocity at the propulsor position, the method is capable of predicting the effect of single and contra-rotating propellers on the boundary-layer flow in the vicinity of the propulsor. The propulsor effect is shown to be insignificant more than one propulsor diameter upstream. (U).

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LIST OF SYMBOLS

A	Area of propulsor annulus
C_f	Local skin-friction coefficient
C_p	Pressure coefficient
ΔC_p	$(C_p)_u - (C_p)_p$
$(C_p)_u$	Pressure coefficient (unpropelled case)
$(C_p)_p$	Pressure coefficient (propelled case)
C_T	Thrust coefficient of propulsor = $T/\frac{1}{2}\rho u_o{}^2 A$
D	Body diameter
D_p	Propulsor diameter
K_T	Thrust coefficient of single propeller = $T/\rho \pi n^2 D_p{}^4$
L	Body length
n	No of revolutions of single propeller per unit time
R_L	Reynolds number based on body length
r_1	Distance from hull along a radius
T	Propeller thrust
U	Velocity component parallel to hull
U_o	Freestream velocity
V	Average velocity through propulsor disc with propulsor operating.
v	Change in average velocity through propulsor annulus due to presence of propulsor.
Δ	Propulsor diffusion ratio = $(V + v)/V$
ρ	Density

INTRODUCTION

A method for predicting the turbulent boundary layer on a body of revolution is described in references 1 and 2. In many practical situations, however, a body of revolution is fitted with control fins and a propulsor. In the present Memorandum the boundary-layer prediction method for a body of revolution with no fins is extended to include a simple representation of a lightly-loaded propulsor.

The prediction method requires knowledge of the average increment in velocity at the position of the propulsor due to the presence of the propulsor, a quantity which is not usually known. According to actuator disc theory for uniform axial velocity, this can be related to the thrust coefficient of the propulsor, which at the design stage is usually a specified parameter or which can be measured. The method should enable predictions to be made of changes in boundary-layer velocity profiles due to both the propulsor and changes in Reynolds number. Such predictions can be used to modify model boundary-layer measurements on a body without propulsor to represent velocity profiles at full scale with propulsor.

2. THEORY OF THE PROPULSOR REPRESENTATION

The boundary-layer calculation method is assessed elsewhere [1, 2]. In general, provided that the flow remains attached, the method gives a reasonable approximation to the velocity profiles on a body of revolution without propulsor. The method iterates between a potential flow calculation (giving a streamwise pressure distribution) and a viscous flow calculation using the given pressure distribution. In the present approach the potential flow calculation is modified to include a representation of a propulsor.

It is well known that the flow field of an actuator disc model of a single propeller [3, 4] operating in a uniform flow can be represented by a semi-infinite system of vortex rings [5]. This has been shown to be equivalent to the flow field produced by a sink distribution over the propeller disc plus a uniform flow downstream of it. In the present approximate approach the propeller is assumed to be uniformly and lightly loaded. Besides the single propeller the theory is also applied to contra-rotating propellers.

It can be shown theoretically, by assuming that the pressure along a surface normal is constant, that the velocity external to a boundary layer in a viscous flow is the same as the tangential component of surface velocity produced by a potential flow over the hull plus displacement thickness. It is assumed in the propulsor representation that this is true both upstream and downstream of the propulsor, which in the potential flow calculation is fitted to the displacement surface. The propulsor is represented by an annular distribution of uniform sinks of area equal to the propulsor annulus, plus a flow which is uniform immediately downstream of it. In practice the propoulsor wake decays to zero at infinity through the action of viscosity, an effect which is not present in an idealised potential flow situation. However the region of prime interest in the present study is the attached boundary layer near the propulsor and the boundary-layer computation is usually terminated about one body length downstream of the tip.

In order to predict the correct values of tangential velocity along the displacement surface, it is assumed that the displacement surface is cylindrical immediately downstream of the propulsor. In the examples studied this assumption was found to be reasonable. Any errors caused by slight convergence or divergence of the surface will usually be small.

The propulsor inflow is specified by prescribing V (the average axial velocity over the propulsor annulus without propulsor operating) and the diffusion ratio Δ which is defined as

$$\Delta = (V + v)/V \qquad (1)$$

where $V + v$ is the average axial velocity through the propulsor annulus with propulsor operating. At model scale Reynolds numbers V can be determined from boundary-layer measurements or a prediction, whilst at full scale it must usually be estimated from a prediction. It is assumed that the equation from actuator disc theory [3, 4],

$$T = 2\rho A_v (V + v) \qquad (2)$$

where A is the area of the propulsor annulus, can be applied to a boundary-layer inflow with the above definitions of V and v. The thrust coefficient C_T, given by

$$C_T = T/\tfrac{1}{2}\rho A U_o^2 \qquad (3)$$

can be expressed in terms of V and v as

$$C_T = 4 v (V + v)/U_o^2 \qquad (4)$$

which can be solved for v given a value of C_T, hence giving a value of Δ. For a single propeller, an alternative thrust coefficient K_T is often defined by

$$K_T = T/\rho n^2 D_p^4 \qquad (5)$$

where D_p is the propeller diameter and n the number of revolutions per unit time. In this case Δ can be calculated given K_T and V.

3. COMPARISON BETWEEN THEORY AND EXPERIMENT

Some axisymmetric boundary-layer measurements on propelled and unpropelled bodies have been obtained by Huang et al. [6] using a laser anemometer. Measurements of axial velocity were made along radii at five axial positions, the farthest downstream of these being very close to the position of the single propeller. Three body shapes were tested, each with the same length to diameter ratio (L/D = 10.97) but with different afterbody shapes. An earlier assessment of the prediction method without a propulsor [2] indicated that good agreement between predicted and measured velocity profiles is usually obtained for slender afterbody shapes, ie those with the angle between the tangent to the body surface and the axis

being less than about 15°. To verify the propulsor induction effect, the most slender afterbody shape of reference 6, known as body 5225-1 was chosen as its maximum angle is 14°.

In reference 6, the value of the propeller thrust coefficient C_T is given as 0.371 but no information is given as to how this value was obtained. From a prediction using the present theory without propeller operating, at Reynolds Number R_L, based on body length, of 5.9×10^6, V/u_o was estimated as 0.65, giving v/U_o from (4) as 0.121 and $\Delta = 1.19$. Figure 1 shows the measured and predicted velocity profiles with and without propeller operating at $R_L = 5.9 \times 10^6$ and axial position $x/L = 0.977$, very close to the propeller position ($x/L = 0.983$). Both measurements and predictions have been corrected, using a method described in reference 2, to represent the velocity component parallel to the hull along a radius. The unpropelled profiles agree well but in the propelled case the values are over-predicted across most of the boundary layer. Values of V/U_o and v/U_o were also obtained by integrating the measured velocity profiles across the boundary layer. V/U_o was close to the predicted value of 0.65, but the value of v/U_o was only 0.078 giving $\Delta = 1.12$ compared with the value above of $\Delta = 1.19$. From (4) the value of C_T required to give this value of Δ is 0.22, only 60% of the quoted value.

To examine this disparity, comparisons were obtained between measurements and predictions of other flow variables as well as velocity profiles. Huang et al obtained measurements at several axial stations of C_p (pressure coefficient), $\Delta C_p = (C_p)_u - (C_p)_p$ (where the subscripts u and p denote the unpropelled and propelled cases respectively) and C_f (the local skin-friction coefficient). Predictions of these quantities along with velocity profiles were obtained with $\Delta = 1.12$ (the value based on measurements of V and v) and with $\Delta = 1.19$ (the value based on predicted V and specified C_T). Both sets of velocity profiles at $x/L = 0.977$ are compared with measurements in figure 1. The agreement is better with $\Delta = 1.12$. Predictions and measurements of C_p and ΔC_p are composed in figure 2 and those of C_f in figure 3. The predictions for $\Delta = 1.12$ agree considerably better with the measurements in figure 2 than those for $\Delta = 1.19$. For C_f (figure 3) neither method agrees well with experiment near the tip of the body in trend or in magnitude, the differences between the predicted propelled and unpropelled cases being less than the measurements in both cases. Measurements of velocity profiles at five different axial positions are compared with predictions for the case $\Delta = 1.12$ in figure 4. The unpropelled measurements agree with the predictions at most positions and the average difference between propelled and unpropelled cases is well predicted. These comparisons suggest that provided the propeller inflow at the propeller position is correct, then the effect of the propeller on the upstream flow is also well-predicted. Both measurements and predictions

suggest that the upstream influence of the propeller is negligible at distances greater than about one propeller diameter.

Some wind tunnel measurements were made at AMTE on a torpedo-shaped body with a hemispherical nose and a conical tail with 10° semi-angle. Values of total velocity were measured along lines normal to the hull using travelling total head and static tubes. The body was fitted with contra-rotating propellers and four tail fins, but a wake survey downstream of the fins revealed that their effect on the flow was restricted to $\pm 20^{\circ}$ on either side of the fins. Predictions with propellers operating were obtained by assuming that the contra-rotating propellers could be represented by a single propeller mid-way between the two. The change in velocity at the propeller position was estimated by calculating the measured changes in velocity at each station and interpolating the results. Predictions and measurements are compared in figure 5. The good agreement implies that the boundary-layer method is capable of predicting the velocity induced by the propeller on the attached flow both upstream and downstream of the propeller. Both predictions and measurements again suggest that the propellers only influence the flow up to about one propulsor diameter upstream. At the station furthest downstream the flow is close to separation. Also at the two stations downstream of the propellers, at the edge of the boundary layer the measured values of velocity drop to below the unpowered values. This effect can be explained by considering conservation of mass. The velocity increment in the boundary layer flow must be compensated by a decrement in the external flow.

4. CONCLUSIONS

A simple representation of a lightly-loaded propulsor has been included in an axisymmetric boundary-layer calculation method. Given the correct change in average velocity at the propulsor position between the propelled and unpropelled cases, the method is shown to give reasonable predictions of the effects of single and contra-rotating propellers on the boundary-layer parameters and the changes in average velocity both upstream and downstream of the propulsor. Both theory and experiment indicate that the influence of the propulsor is negligible more than about one propulsor diameter upstream of the propulsor.

Only a very small amount of experimental data is available for comparison. The one set of data where a value of thrust coefficient is supplied suggests that the potential-flow actuator-disc relation between thrust coefficient and change in velocity due to the propulsor cannot be applied to a boundary-layer flow. However, before any definite conclusion can be reached, there is a need for more boundary-layer measurements on bodies of revolution with and without propulsor operating coupled with measurements of propulsor thrust coefficient.

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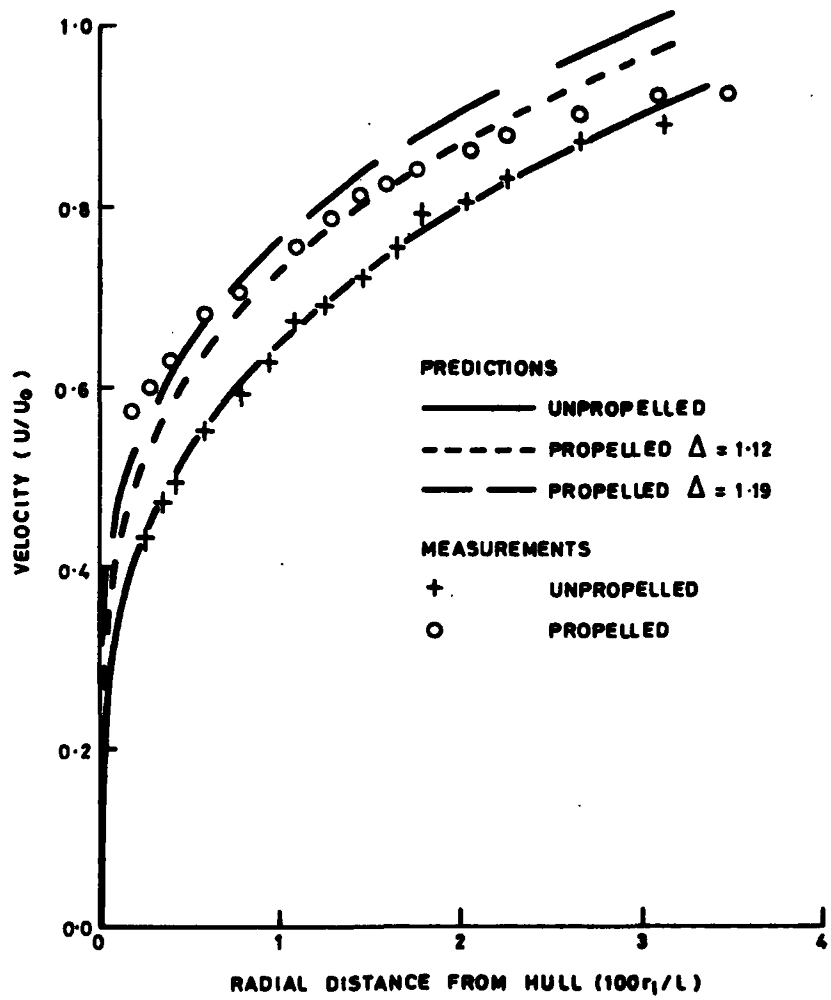

FIG. 1 VELOCITY PROFILES ON BODY 5225-1 AT $x/L = 0{\cdot}977$

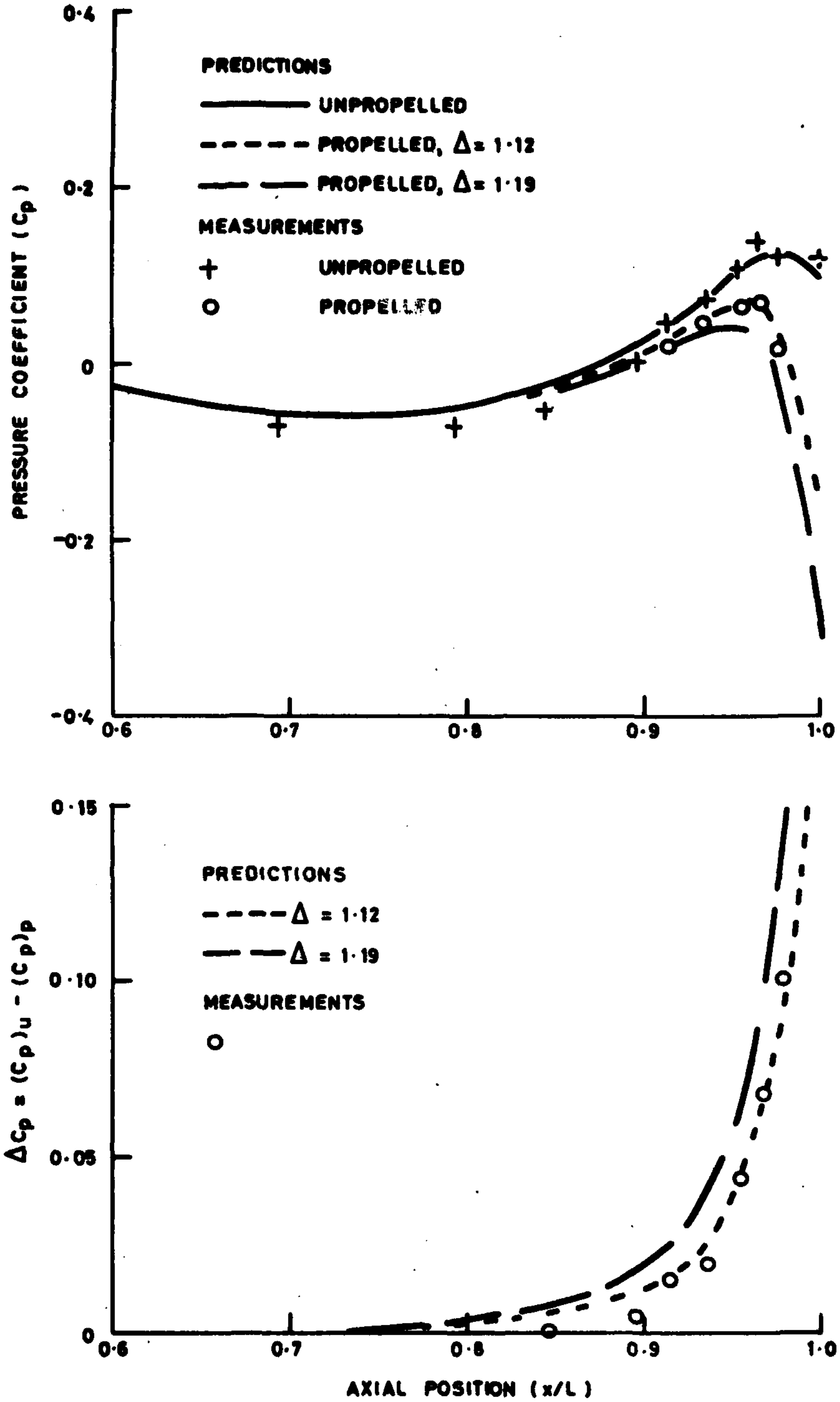

FIG. 2 THE VARIATION OF PRESSURE COEFFICIENT WITH AXIAL POSITION ON BODY 5225-1

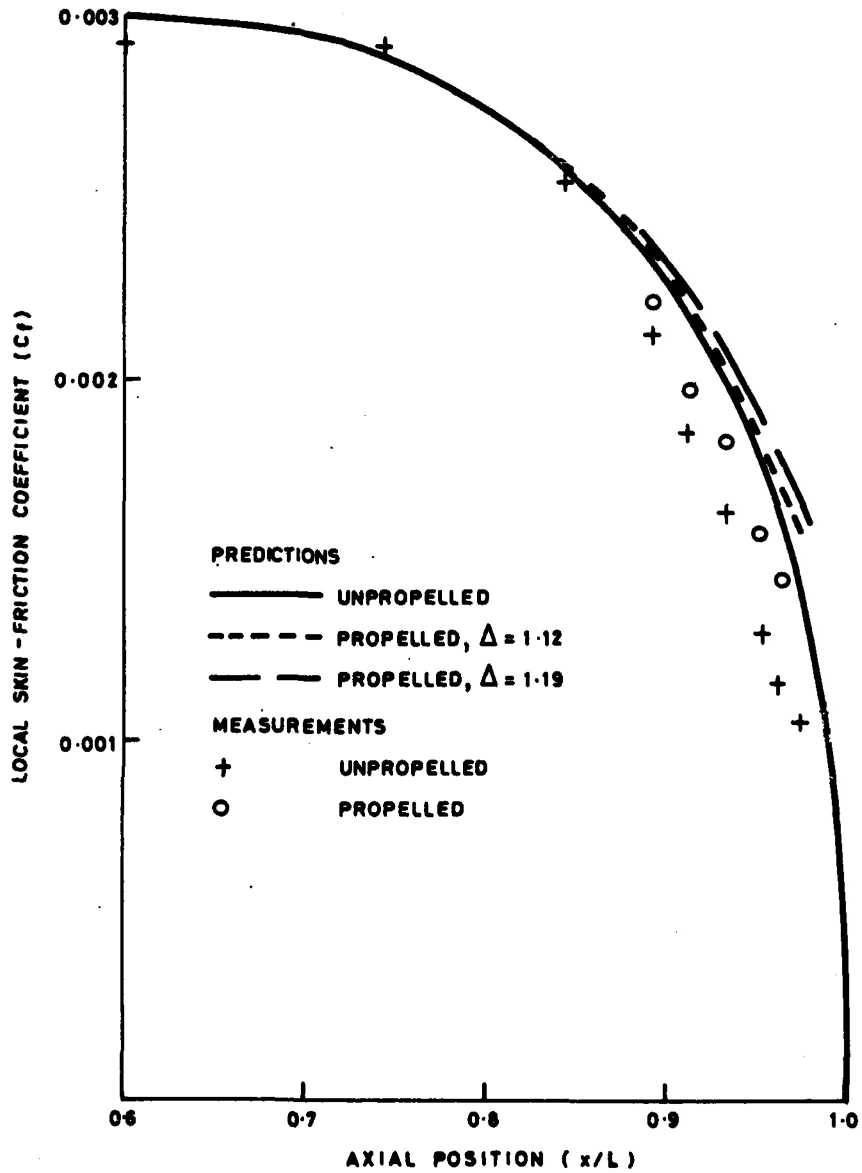

FIG. 3 THE VARIATION OF LOCAL SKIN-FRICTION COEFFICIENT WITH AXIAL POSITION ON BODY 4225-1

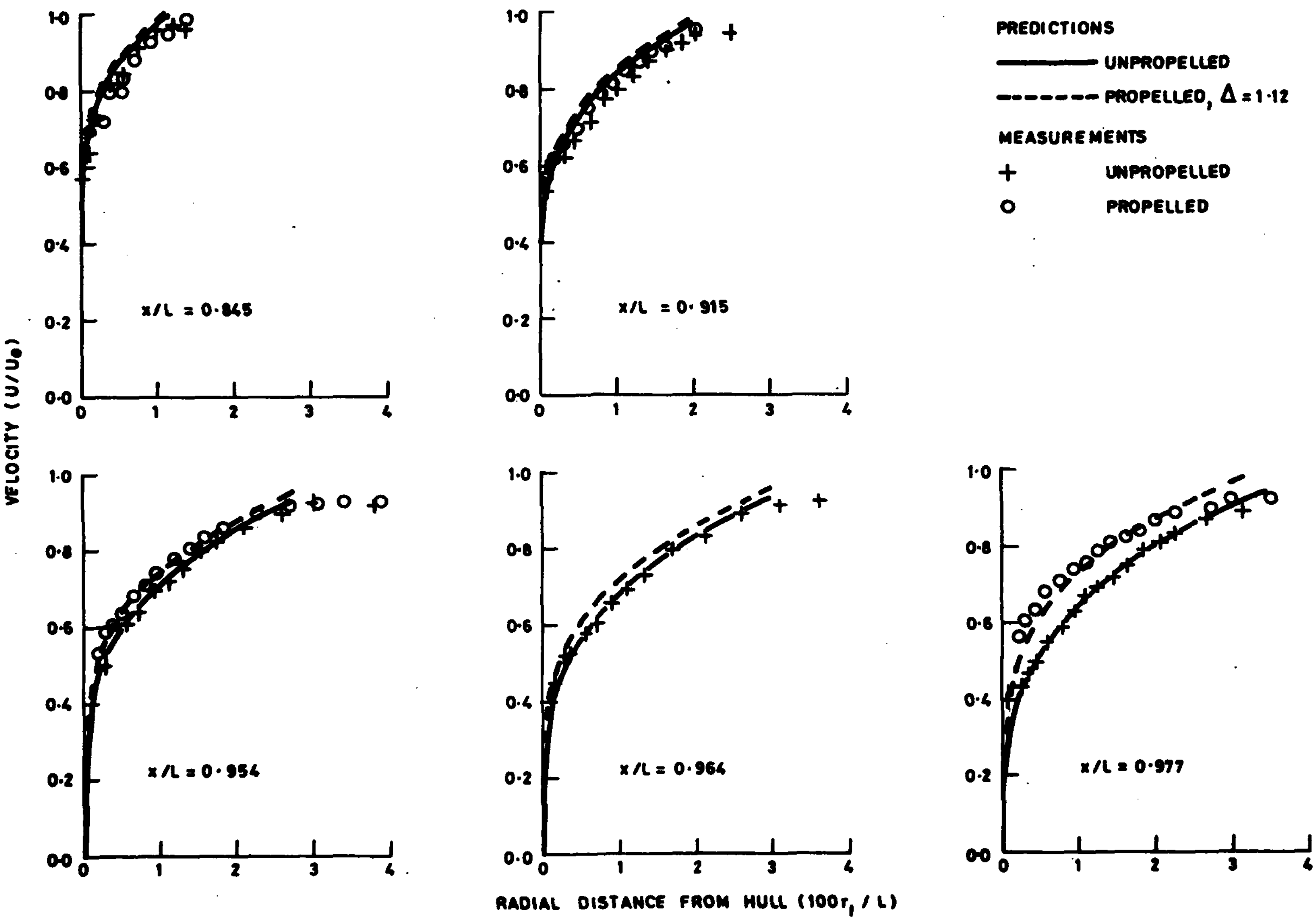

FIG. 4 VELOCITY PREDICTIONS AND MEASUREMENTS ON BODY 5225-1

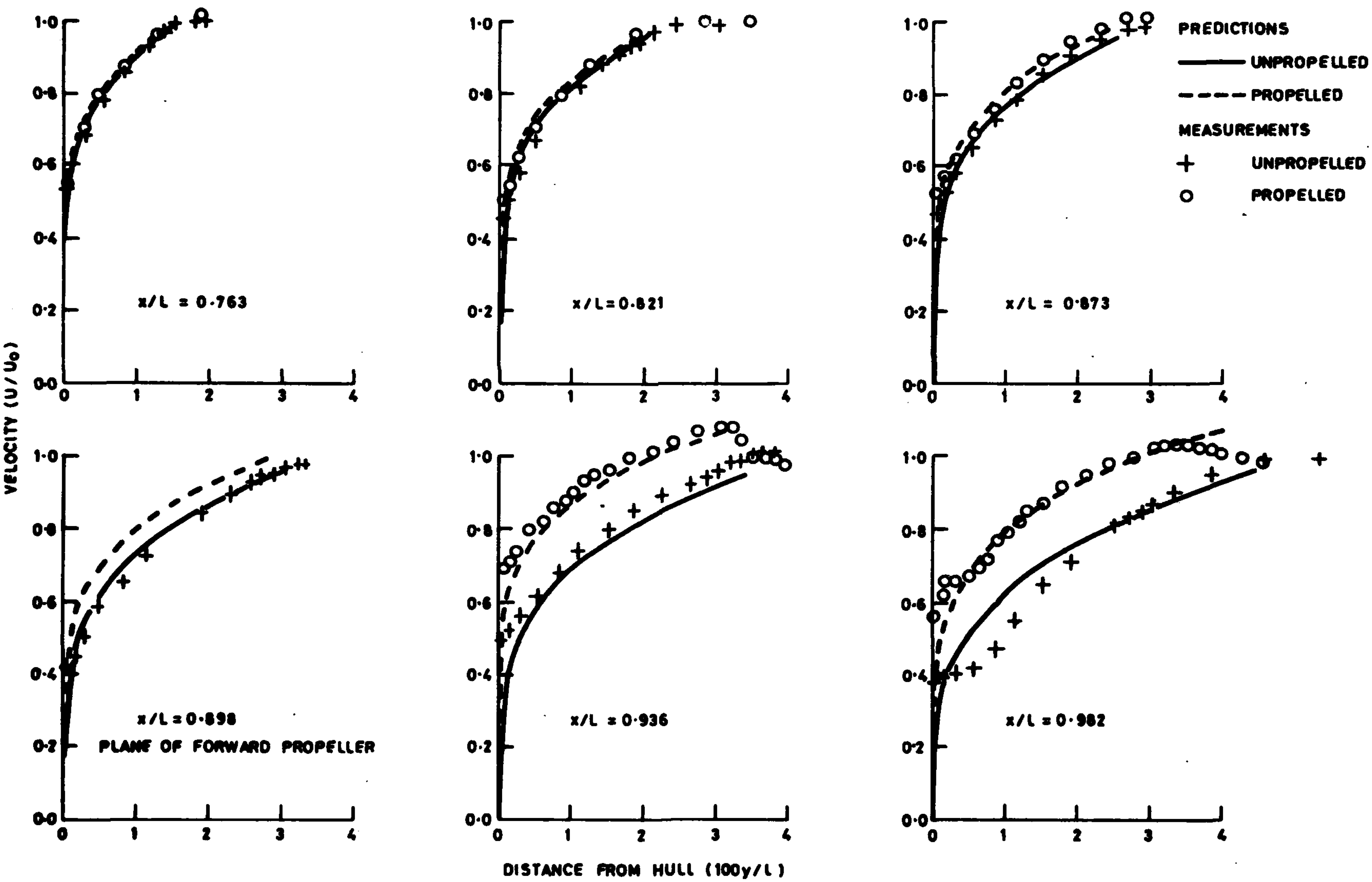

FIG. 5 VELOCITY PREDICTIONS AND MEASUREMENTS ON A TORPEDO MODEL